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Economic operation of wind farm integrated system considering voltage stability☆

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ABSTRACT

Wind farms interconnected to power system bring new challenges to power system economic operation. It is imperative to study how to solve optimal power flow (OPF) formulation with wind farms. In this paper, a multi-period optimal power flow (DOPF) is studied based on traditional OPF algorithm. According to the characteristic equations of asynchronous generator, the paper deduces a new algorithm that fits the DOPF formulation with wind farms. Based on the primal–dual interior point algorithm (PDIPM), a new modified algorithm is proposed. Besides, the voltage stability indicator, L-indicator, is also introduced into DOPF to demonstrate voltage stability of power system after wind farms incorporation. By taking SVC reactive power compensation into account, the paper analyzes its influences on system voltage stability. In addition, four different static load models are researched to reveal their effects on system-operating characteristics. An example shows the algorithm's effectiveness and computation performance of the proposed method and several conclusions are obtained as well.

1. Introduction

Wind resource is a kind of renewable energy, and becomes more and more important in many countries. China government is planning to obtain over 10% of electricity from wind energy, particularly in the Northwest and coastline of Southeast. Wind power has its own characteristics, such as discreteness, randomness, and uncontrollability. With the increase of power capacity of future wind farms in power system, the study of how big integrated wind farms affect power system operation becomes quite important. Some of these challenges are voltage control, voltage stability of power system, reactive power management, dynamic power swing stability, power quality, and behavior following disturbances in the power grid, etc [1–4].

Application of optimal power flow (OPF) in power utilities has brought considerable economic and social profits [5,6]. Being a kind of renewable energy, wind energy would contribute greatly to energy crisis and OPF with wind farms integration can be harnessed to improve system economy as well as to evaluate how wind farms affect power system.

Traditional OPF solves the optimization formulation to minimize or maximize objective functions in a single time period without considering the inherent relations of different periods. While, in fact, power system is dynamic and static methods may not acquire precise results. Besides, with load in china increasing steadily and rapidly during recent years, the margin between peak load and valley load has been getting big step by step. Moreover, as power load is also time-dependent, constraints of output variation rates and regulating capacity of generators in system restrain the ability of power system to balance load changes [7]. Likely, because outputs of wind farms are also changing along with wind speed, generators' regulating rates may reach their power limits. Static methods may not be able to solve such kind of problem. Therefore, in this paper, a dynamic method is proposed to solve OPF problem with wind farms (DOPF).

The crux of solving above formulation is how to handle wind turbines (WTs) properly without losing calculation precision and speed. In steady state analysis, nodes integrating WTs are often treated as PQ nodes [8,9], but this approach cannot match with actual situation. Generally, traditional asynchronous generators are used as WTs in China. Accounting for the high costs of OLTC, WTs are usually integrated to power system with traditional step-up transformers. But asynchronous generators have to absorb reactive power to erect their magnetic fields and it might worsen voltage stability [10,11]. In cases when Var compensation is indispensable in power system, usually SVC is utilized as main compensation device.

Up to now, numerous researches have been done about OPF with wind farms. Paper [12], making use of fuzzy theory, establishes a fuzzy model for power system economic dispatch

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with wind farms, which takes stochastic feature of wind farm output into account. Subsequently particle swarm optimization (PSO) is ameliorated to solve the problem, but its calculating precision is not satisfying. In Ref. [13], a chance-constrained active power optimization is introduced and WTs' outputs are treated as stochastic variables. Papers [14,15] employ a multi-stage power flow (PF) model to deal with random behavior of wind speed. The expectation of the wind power active power output of every stage, according to forecasting methods, is calculated for PF. Based on the Q–V equation of WTs, two papers employ a joint iteration method to solve PF and OPF formulations. While such a joint iterative method may increase CPU time.

In order to achieve a compromise between precision and speed of algorithm, we propose an improved primal–dual interior point algorithm (PDIPM) to solve the DOPF with wind farms. This presented algorithm, based on simplified asynchronous generator model, fully accounts for relationship between WT reactive power and its voltage. It can well handle contradiction between precision and iteration speed, and may keep the advantages of the primal–dual interior point algorithm (PDIPM). Additionally, a voltage stability indicator, L-indicator, is introduced into the DOPF formulation. This indicator can effectively indicate voltage stability of different nodes. Besides, traditional static load models are also investigated to reveal their effects on system-operating characteristics.

This paper is organized as follow: Section 2 presents several relating models, including simplified WT model, aerodynamic model, multi-stage strategy, SVC model, and static load model. In Section 3, the voltage stability indicator is introduced. A multi-stage DOPF formulation with wind farms and an improved PDIPM with its calculating flow are presented in Section 4. In Section 5, the improved PDPIM is used to solve the multi-period DOPF formulation. An example of IEEE-14-bus test system illustrates availability, effectiveness and correctness of the presented method. Finally, several important conclusions are given.

2. Several relating models

2.1. Wind turbine model

In most parts of China, WTs are mainly asynchronous generators, which absorb kinetic energy to produce electrical energy and amount of reactive power to establish their magnetic fields.

If stator and rotator copper loss and leakage inductive reactance loss are neglected, a simplified Γ type equivalent circuit can be gotten by moving exciting circuit to left side of the model, as indicated in Fig. 1. From such model, the following equations can be obtained [10,16]:

$$V = \sqrt{\frac{-P_e\left(s^2x^2 + r_2^2\right)}{r_2 s}} \tag{1}$$

$$Q_e = -\left(\frac{V^2}{x_m} + \frac{P_e(x_1 + x_2)}{r_2}s\right) \tag{2}$$

From Eq. (1), we can get

$$s = \frac{\left(-V^2r_2 + \sqrt{V^4r_2^2 - 4P_e(x_1+x_2)^2r_2^2}\right)}{2P_e(x_1+x_2)^2} \tag{3}$$

The asynchronous Q–V characteristic can be obtained by integrating Eq. (2) into Eq. (3):

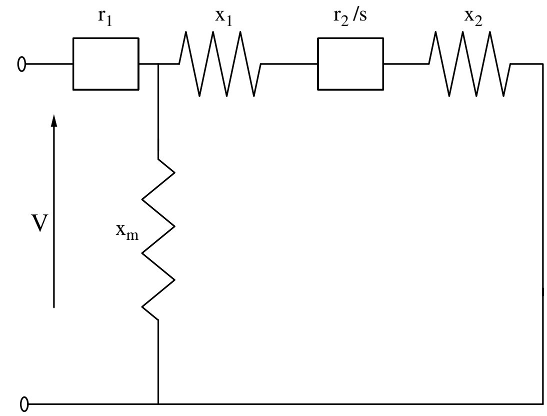

Fig. 1. Simplified equivalent circuit of asynchronous generator.

$$Q_e = f(V) = -\frac{V^2}{x_m} + \frac{-V^2 + \sqrt{V^4 - 4P_e^2(x_1+x_2)^2}}{2x_k} \tag{4}$$

where V and P_e represent generator voltage and wind farm active power. If P_e is constant, according to Eq. (4), Q_e that asynchronous generator absorbs during operation has a close relationship with its voltage V.

2.2. Aerodynamic model

The presented aerodynamic model is based on aerodynamic efficiency C_p. For a given WT rotor, C_p depends on the tip speed ratio, i.e. $C_p = C_p(\lambda)$. λ is defined as the ratio between blade tip speed and wind speed, which means that with a certain blade radius R, λ is defined as

$$\lambda = \frac{\omega R}{v} \tag{5}$$

where ω is angle velocity of blade at wind speed v. Aerodynamic power P_m is determined by

$$P_m = \frac{1}{2}\rho\pi R^2 v^3 C_p \tag{6}$$

where ρ is air density. The relationship between C_p and λ can be derived from experiment or numerical interpolation based on experiment data. Fig. 2 is their typical relationship curve.

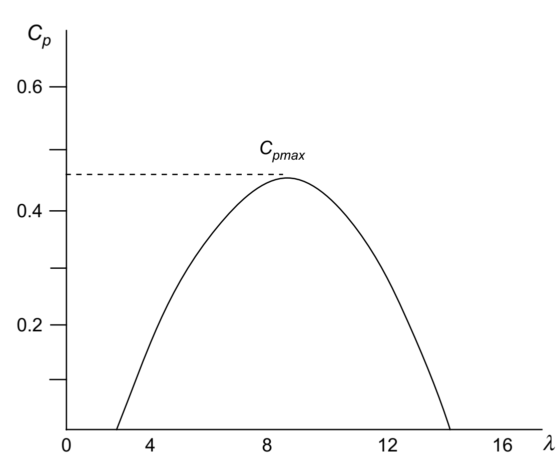

Fig. 2. Relationship curve between C_p and λ.